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SOME EXAMPLES OF THE EFFECTS OF THE POLEWARD F-LAYER TROUGH WAL--ETC(U)
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SOME EXAMPLES OF THE EFFECTS OF THE POLEWARD F-LAYER TROUGH WALL ON GROUND RANGE AND AZIMUTH DETERMINATION IN AN OTH BACKSCATTER SYSTEM

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Scientific Report No. 1

February 1977

Approved for public release; distribution unlimited

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFGL-TR-77-0075

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): Some Examples of the Effects of the Poleward F-layer Trough Wall on Ground Range and Azimuth Determination in an OTH Backscatter System.

5. TYPE OF REPORT & PERIOD COVERED: Scientific Report-1, Oct 1976 - Jan 1977

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): Barbara M./Langworthy

8. CONTRACT OR GRANT NUMBER(s): F19628-76-C-0296

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Parke Mathematical Laboratories, Inc.
One River Road Box A
Carlisle, Massachusetts 01741

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
62101F
76630901

11. CONTROLLING OFFICE NAME AND ADDRESS:
Air Force Geophysics Laboratory
Hanscom AFB, Massachusetts 01731
Contract Monitor: Jurgen Buchau (PHI)

12. REPORT DATE: February 1977

13. NUMBER OF PAGES: 52

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
Rept. for Oct 76 - Jan 77, 51p.

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report):
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):

18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
Three-dimensional Ray Tracing
Arctic Radio Propagation
OTH Backscatter Simulation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

This report describes the effects of a realistic trough wall model on azimuth and range errors expected for a OTH radar system. The strong north-south electron density gradients found in the trough wall result in considerable deviations from great circle propagation. Using a three-dimensional ray tracing program landing points of rays transmitted at 5 MHz were determined as a function of the initial azimuth and elevation angle. Using a spherical model ionosphere as reference, the effects of the realistic trough wall were expressed as range and azimuth errors. To determine the dependence of range and azimuth →

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errors on the variability of the trough wall, upper and lower quartile values of the model were also used in the computations. Power calculations indicate, that focusing effects > 15 dB can be expected for selected bundles of rays which just enter the trough wall.

FOREWORD

This document is the first scientific report on AFGL Contract F19628-76-C-0296. The work described herein represents the completion of the following contract items:

a. Modify the electron density routine of the existing 3-D ray tracing program to accept a standardized trough wall profile along an arbitrary smooth curve given in geographic coordinates.

b. Using the trough wall model provided by LIB, compute the effects of 3 to 5 trough wall configurations describing median conditions, and moderate and extreme deviations thereof, on frequencies in the 5 to 10 MHz range. A minimum of four boresights for a narrow beam antenna will be selected for the computations. The range/azimuth errors and the relative energy density of the propagated beam in the landing area will be determined and shown as a function of boresight, frequency, and chosen trough wall model.

Use was made herein of work performed under AFCRL Contracts F19628-73-C-0307 and F19628-76-C-0029.

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1. Introduction

The presence of the auroral oval with its sharp horizontal gradients especially in the region of the poleward F-layer trough wall causes large azimuthal deviations from the great circle path for radio waves in the HF band. It furthermore drastically changes the range of a ray to its landing point, if compared with a case of a homogeneous, horizontally stratified ionosphere. For the case of an OTH backscatter situation this results in both range and azimuth errors of the detected target unless corrections for the effect of the gradients are included in the target registration process. Using the AFGL three-dimensional ray tracing computer program (Langworthy and Barrett, 1975), various cross-sections derived from a new trough wall model have been simulated and backscatter results have been tabulated to give an indication of anticipated deviation in ground range and azimuth. The power with which these signals may be returned relative to signals not experiencing effects of gradients associated with the edge of the auroral oval has also been determined.

The data used to simulate the trough wall throughout this report is based on a model derived from Alouette topside ionograms.

2. Ionospheric Model

In order to determine the magnitude of range and azimuth errors, which an OTH system will experience if operating in the vicinity of the poleward F-layer trough wall, 3D ray tracing technique was applied to a new model of the trough wall (Pike, 1976). The location of the equatorward edge of the poleward trough wall is specified by a series of points in the geographic coordinate system. These points are then converted to the dipolar geomagnetic system for use with the ray trace program. The location of the trough wall is assumed to be composed of the great circle segments which connect the input points. Variations in the plasma frequency in the horizontal direction then become a function of the distance from the trough wall. Distance is taken to be positive north of the wall base and negative for points to the south. The trough wall used for the current study is shown in Figure 1. Details of the computer program which produces the coordinates for the trough wall, program WALL, are given in Appendix A.

The parameters which vary with the distance from the trough wall are the F-layer and E-layer maximum electron density values. These values are given in terms of critical frequencies (foE, foF2 = maximum plasma frequency of the respective layer) or in $N_e$max (electrons/cm^3 for the respective layer maximum), where the two terms are related by the formula:

$$N_e\max = 12400. \cdot fo^2.$$

The foE value varies from 0.1 MHz south of the trough wall to 2.5 MHz north of the trough wall; the height of the maximum electron density (h max) is assumed to be 120 km. The foF2 values north and south of the trough wall are input quantities to the ray trace program as is the width (or steepness) of the wall.

Variation across the trough wall is taken to be linear in the square of the plasma frequency which is equivalent to a linear variation in the electron density. The height of the F2 layer maximum is taken to be constant at 350 km. Electron density variation across the trough wall is given in Figure 2.

FIGURE 1. GEOGRAPHIC LOCATION OF THE TROUGH WALL AT 06 UT

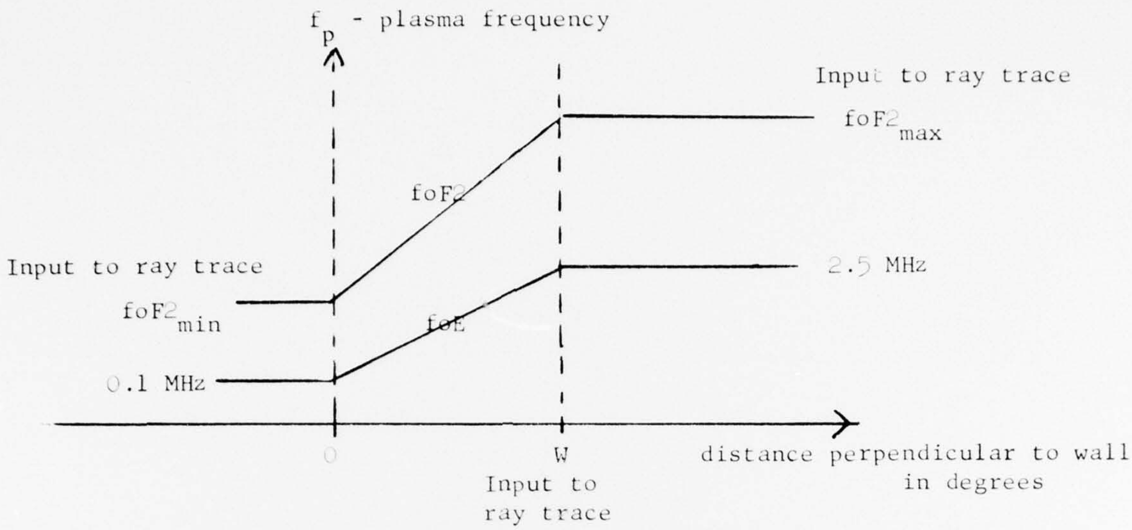


Figure 2. Variation of foE and foF2 across the Trough Wall

Here $foF2_{min}$ is the foF2 (in MHz) at the bottom of the trough and $foF2_{max}$ is the foF2 at the top of the trough. W is the width of the trough wall in degrees.

The various trough wall models examined in this study are listed in Table 1. They were derived from a trough wall model determined by Pike (1976) from Alouette topside ionograms.

Table 1. Trough Wall Models Used

Trough	$foF2_{max}$ in MHz	$foF2_{min}$ in MHz	W in degrees
I	3.81	1.97	3.0
II	3.11	1.97	3.0
III	4.58	1.97	3.0
IV	2.34	1.61	1.5
V	4.92	1.61	3.8

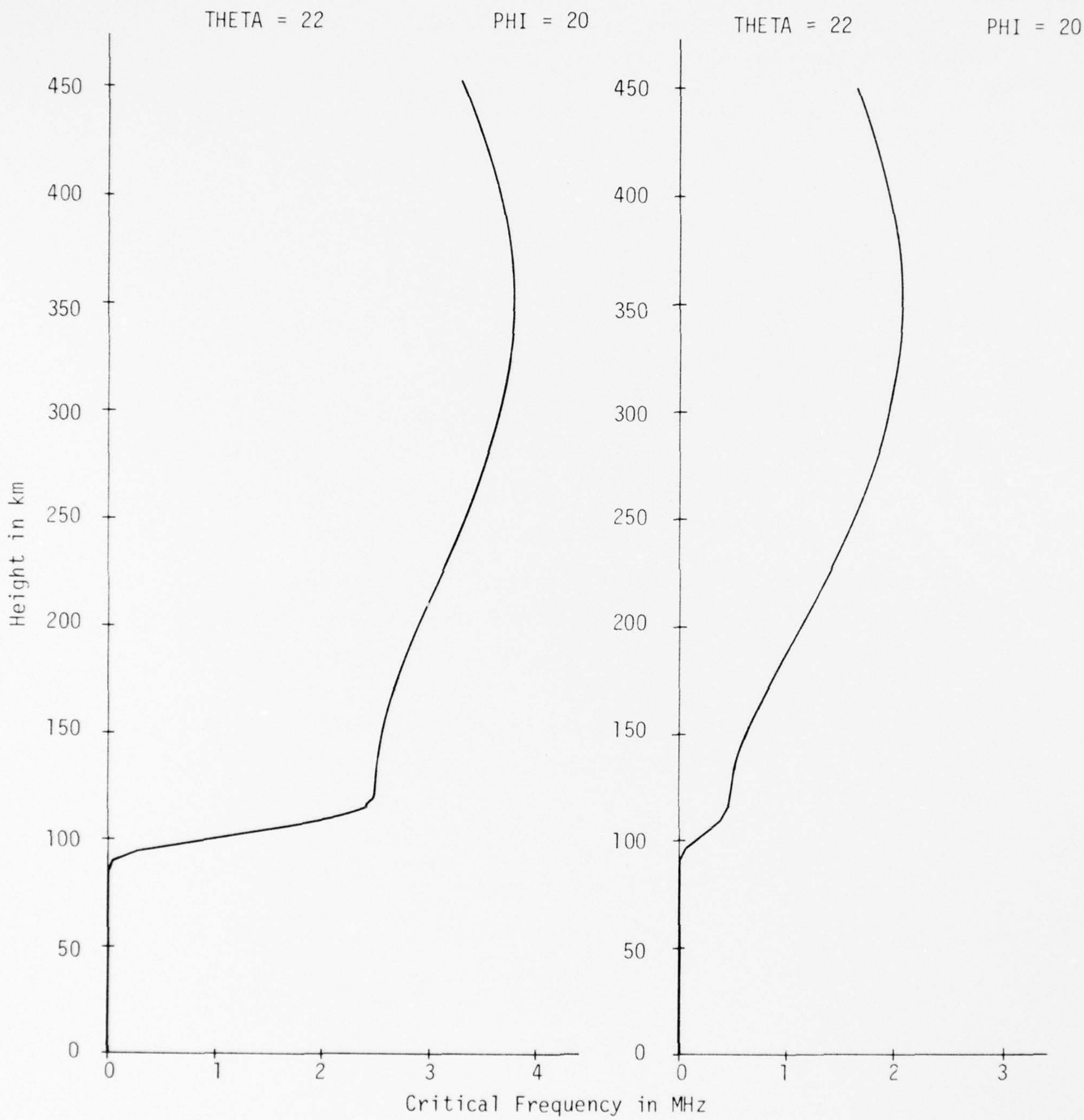


FIGURE 3. VERTICAL PROFILES OF PLASMA FREQUENCY PRODUCED BY SUBROUTINE BCHAP

Model I is the median model, II and III are derived from the upper and lower quartiles of the model gradient, while models IV (most shallow trough), and V (steepest and widest trough wall) are extremes determined from the model.

The vertical variation of the plasma frequency is broken into two segments. Up to the E-layer maximum at 120 km., it is composed of a Chapman layer with a scale height of 10 km. From 120 km. to 350 km. the variation is sine squared in the square of the plasma frequency, i.e.

$$f_p^2 = f_E^2 + (f_{F_{max}}^2 - f_E^2) \cdot \sin^2 H$$

where $H = \frac{\pi}{2} \frac{h - h_{maxE}}{h_{maxF} - h_{maxE}} = \frac{\pi}{2} \frac{h-120.}{230.}$

h is the height in km.

Sample vertical profiles are given in Figure 3. Details on the electron density model, subroutine BCHAP, are given in Appendix B.

The sine squared segment from 120 to 350 km. was used because it was felt that this is a more realistic presentation of the polar ionosphere. This approach made the model less sensitive to variation in the height of the F2 layer than it would be in a Chapman model. Detailed comparisons of the two models are given in Section 3.1. A sketch of the two types of profiles is given in Figure 4.

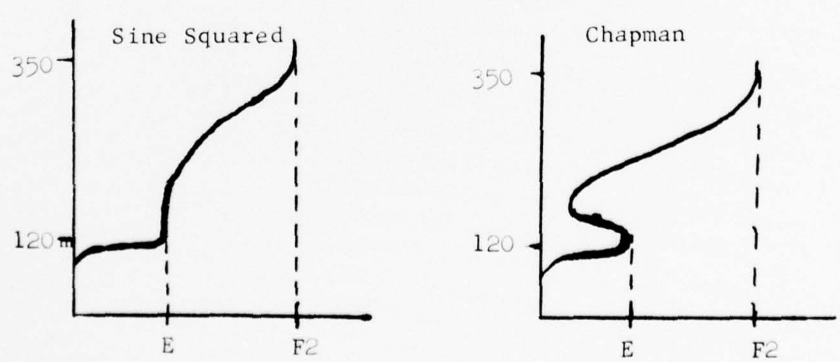


Figure 4. Comparison of Sine Squared and Chapman Vertical Profiles

3. Displays Used

Since the quantity which the OTH backscatter system yields as an indication of target range is the group delay, the group delay must then be converted to ground range. As a possible model for determining ground range from group path length, the sine squared model with an F-layer maximum of 3.0 MHz at 350 km. and an E-layer maximum of 0.1 MHz at 120 km. was used. The curve of group path versus ground range for a transmission frequency of 5 MHz is given in Figure 5.

To get a measure of the deviation in azimuth angle and error in ground range caused by the trough wall model, ray tracing results from the disturbed models previously described were compared with results from the horizontally stratified 3 MHz model described above. (3 MHz was considered a reasonable choice, since it is well within the range of foF2 values to the north of the pole-ward wall model, as shown under $foF2_{max}$ in Table 1. It also is a reasonable value, if the standard ITS-78 foF2 map would be considered the basis for the computation of radar range.) The comparison of range and azimuth results for computations using the realistic and the horizontally stratified models was made for several frequencies (4 to 9 MHz), a selected azimuth range of transmissions (26.5^o to 42^o East of North in the geographic coordinate system), and for elevation angle from 0^o to a maximum of 30^o.

The procedure for computing range errors was to consider as a reference the range versus group path derived from the 3 MHz model as given in Figure 5. For instance, for a transmission frequency of 5 MHz, an elevation angle of 5^o, and an azimuth angle of 36.5^o, the model referred to as Trough I gave a group path length of 2644 km. and a ground range of 2295 km. The 3.0 MHz standard model would yield a ground range of 2564 km. for a group path length of 2644 km. meaning that the ground range of the target determined from a horizontally stratified model was actually 269 km. longer than the actual ground range. Thus the range

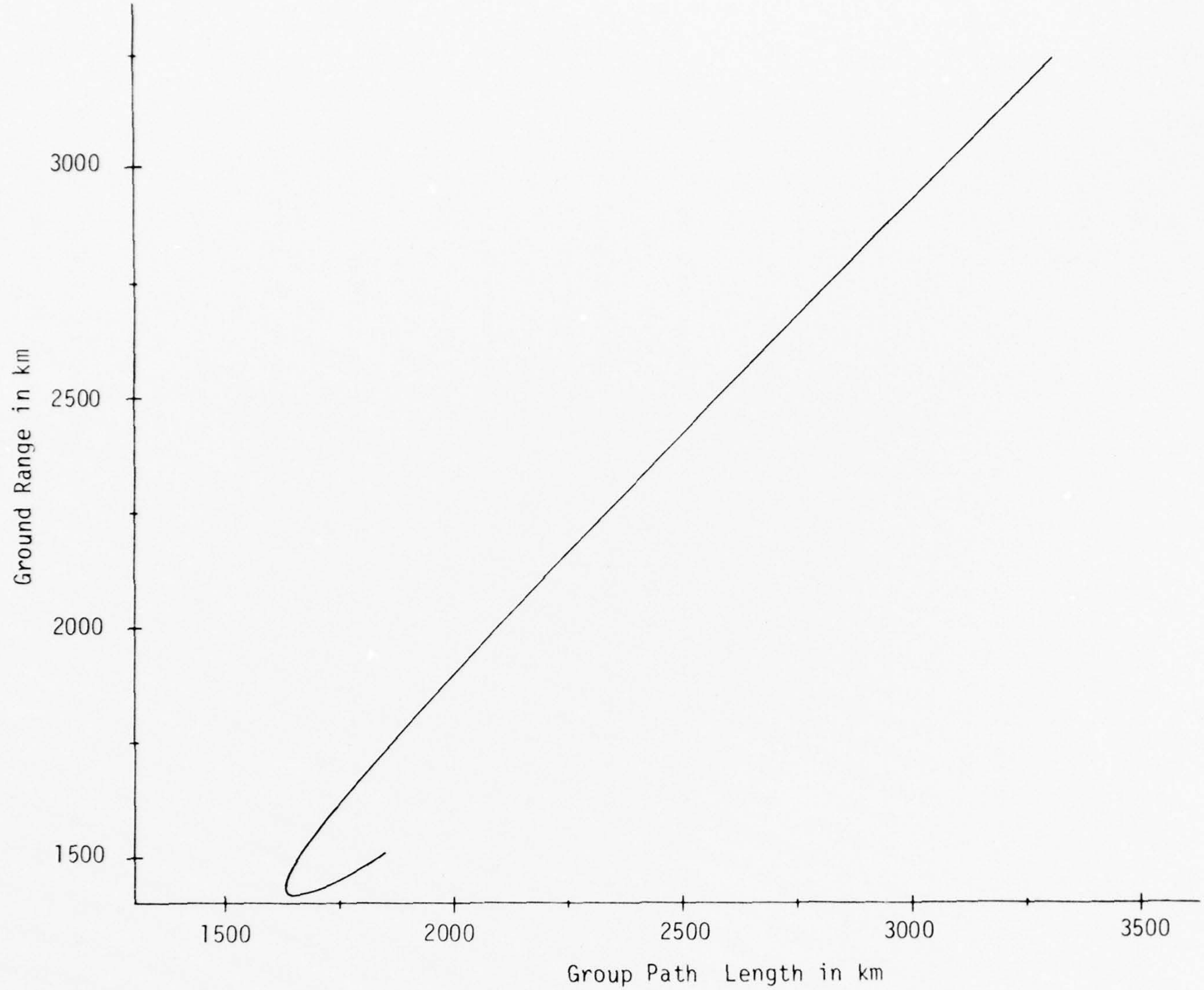


FIGURE 5. GROUND RANGE VERSUS GROUP PATH LENGTH FOR THE 3.0 MHz STANDARD TRANSMISSION FREQUENCY - 5 MHz

error, which would be observed if a realistic model were not available and radar range computations were based on a (reasonable) 3 MHz stratified model, would be +269 km.

A similar procedure was followed in estimating the power difference for the return from a target whose path was influenced by the trough against that of a target that was observed via a 3 MHz horizontally stratified ionosphere (outside the trough wall), using the 3 MHz standard ionosphere. The power level loss was computed as a function of group path length as shown in Figure 6. The power level for any given trough model, frequency, elevation, and azimuth angle was then compared against the standard according to its group path length. In this way it was determined whether the target would appear stronger or weaker as a result of trough bending, and by how much. Details on the power calculations are given in Section 3.2.

3.1 Comparison of Sine Squared Versus Chapman Profile

Before using the 3.0 MHz sine squared layer with its maximum at 350 km. as the standard for determining the ground range and power as a function of group path, the curves were also computed for foF2 = 2.5 and 3.5 MHz (Figures 7 and 10) and for the 3.0 MHz case with the maximum at 300 and 400 km. (Figures 8 and 11).

When the value of foF2 was varied, the skip distance varied considerably as could be expected, but the ground range derived from a given group path varied by less than 50 km with the change of foF2 from 2.5 to 3.5 MHz. The power values for a given group path length varied by 5 dB for values away from the skip distance.

When the height of the F layer maximum was varied for the case of 3.0 MHz, the skip distance varied little. The ground range for a given group path varied by less than 30 km in most areas and the power loss varied by less than 2 dB for elevation angles below the skip elevation angles.

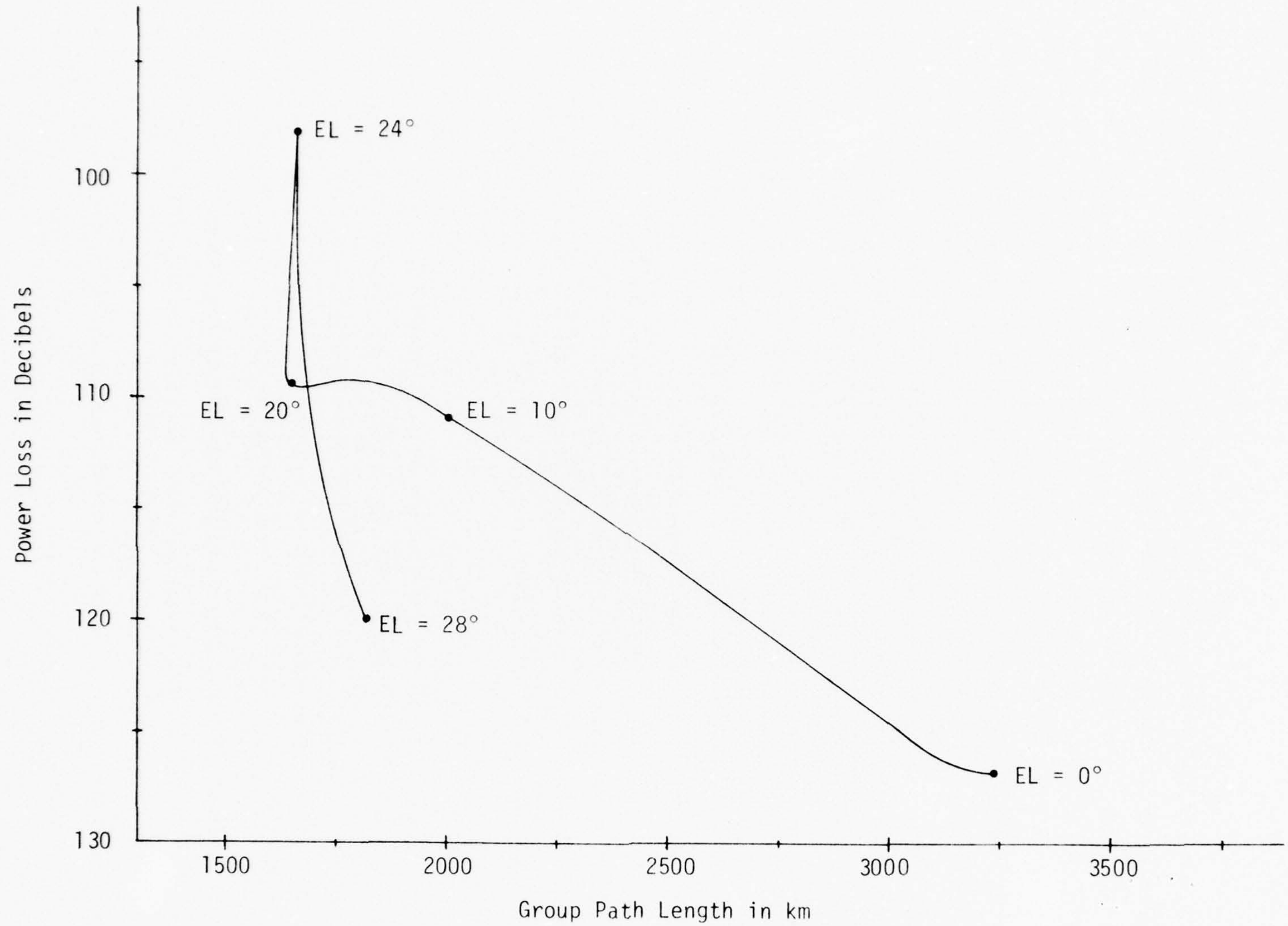


FIGURE 6. POWER LOSS VERSUS GROUP PATH LENGTH FOR THE 3.0 MHz STANDARD TRANSMISSION FREQUENCY - 5 MHz

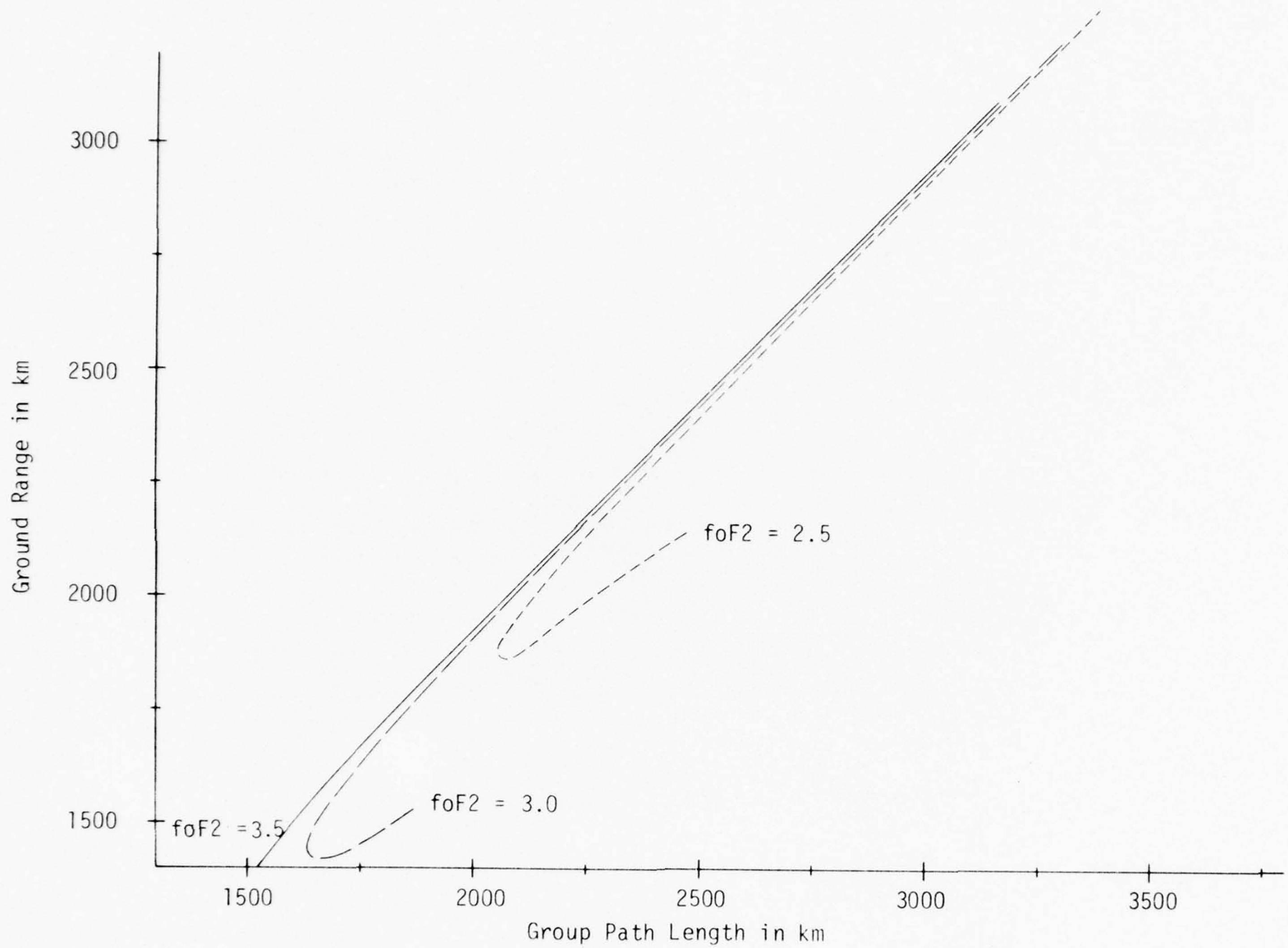


FIGURE 7. GROUND RANGE VERSUS GROUP PATH LENGTH FOR SINE SQUARED PROFILES WITH foF2 = 2.5, 3.0, AND 3.5 MHz LOCATED AT 350 km. TRANSMISSION FREQUENCY IS 5 MHz.

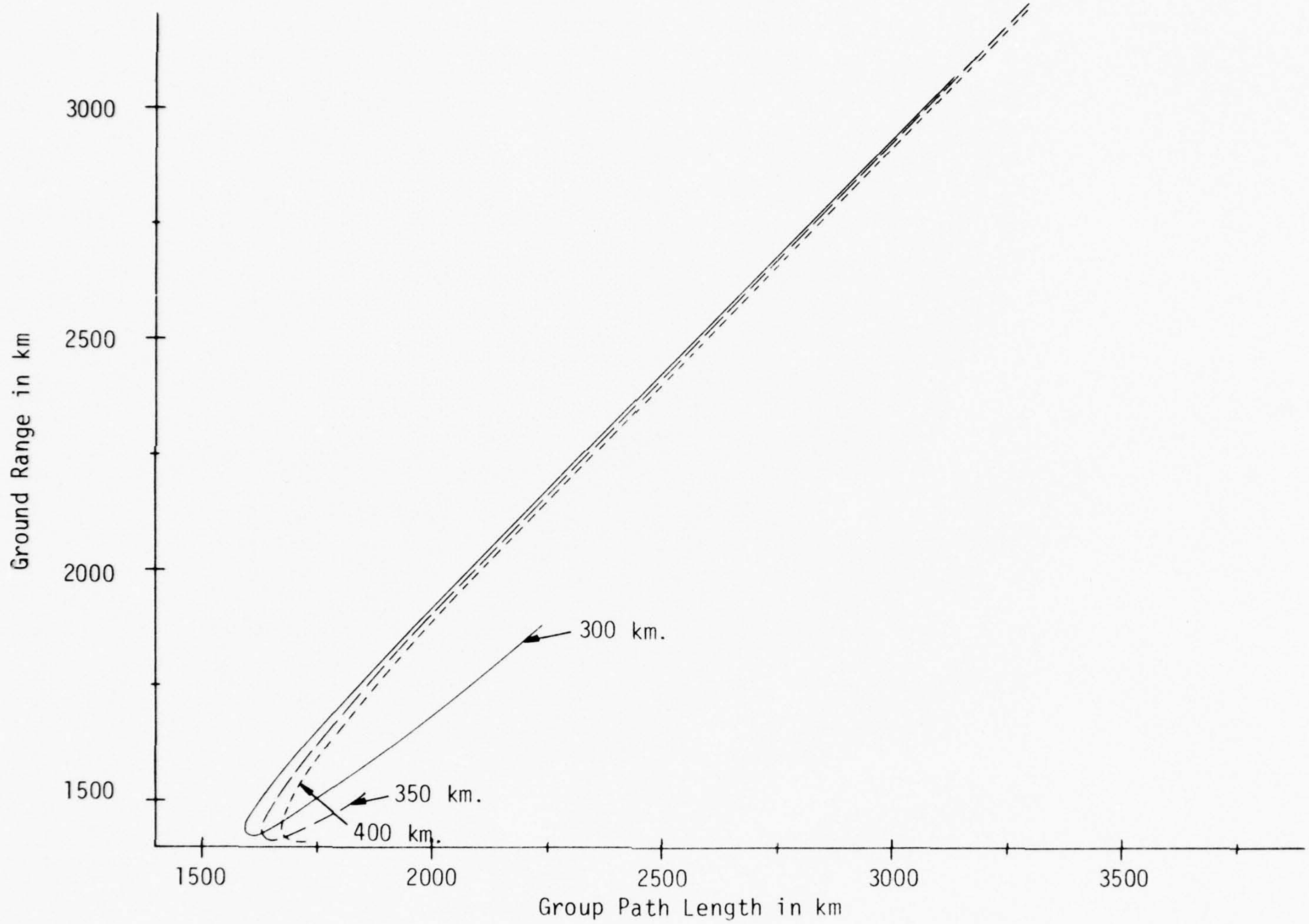


FIGURE 8. GROUND RANGE VERSUS GROUP PATH LENGTH FOR SINE SQUARED PROFILES WITH foF2 = 3.0 MHz LOCATED AT 300, 350, AND 400 km.
TRANSMISSION FREQUENCY IS 5 MHz.

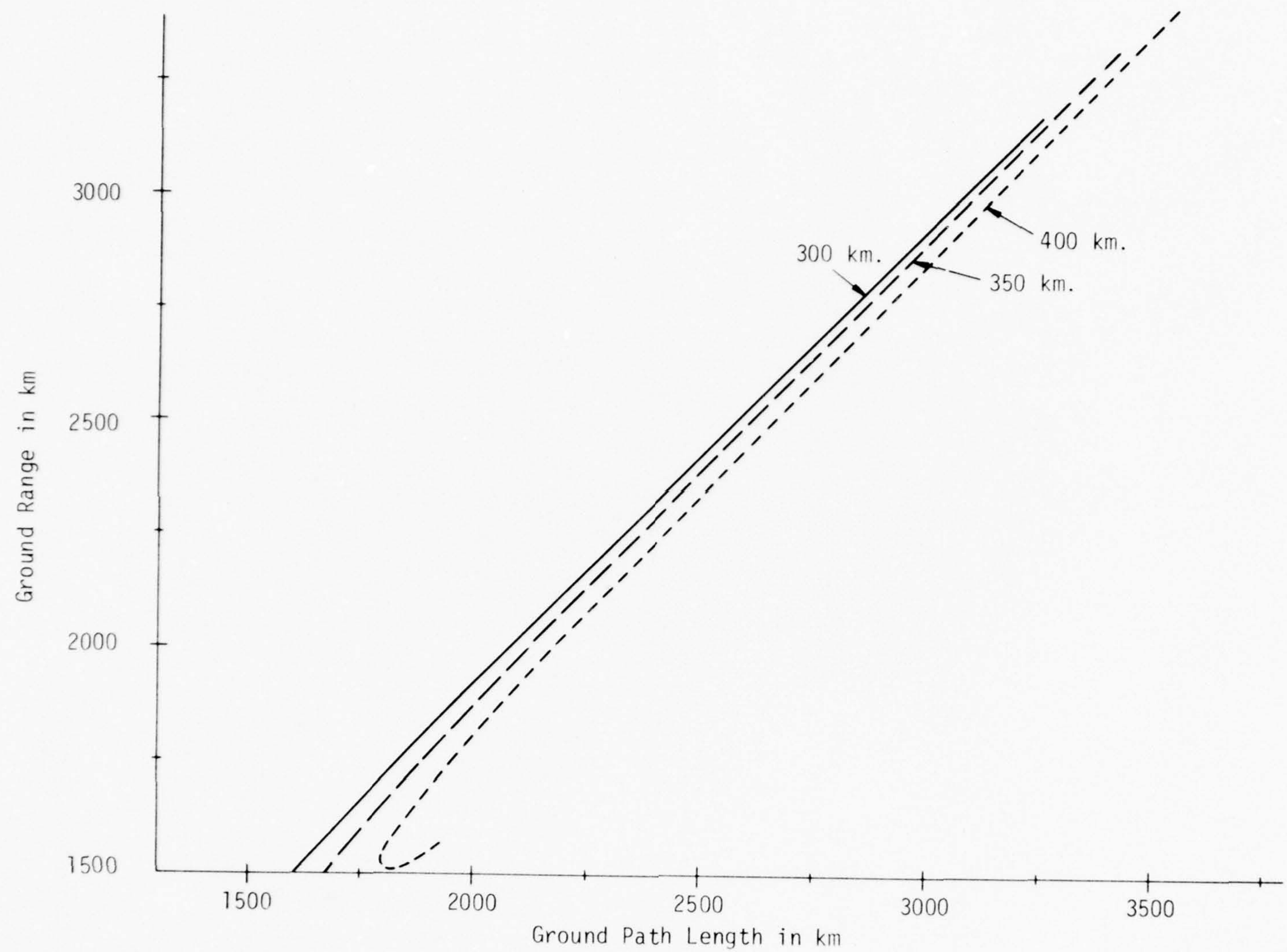


FIGURE 9. GROUND RANGE VERSUS GROUP PATH LENGTH FOR CHAPMAN PROFILES WITH foF2 = 3.0 MHz LOCATED at 300, 350, AND 400 km.
TRANSMISSION FREQUENCY IS 5 MHz.

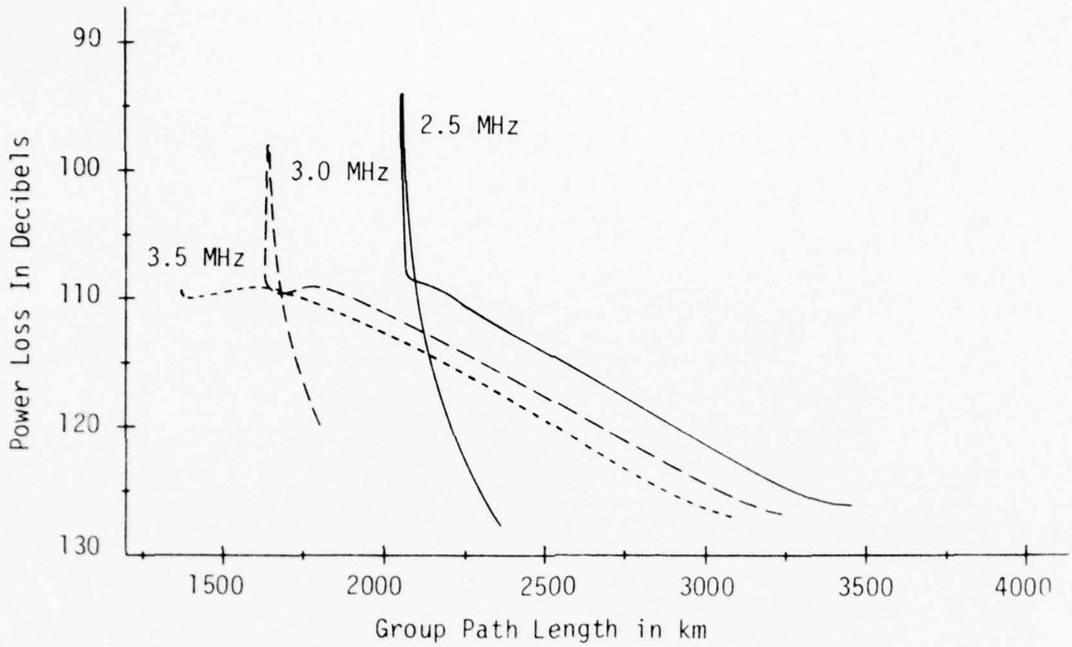


FIGURE 10. POWER LOSS VERSUS GROUP PATH LENGTH FOR SINE SQUARED PROFILES WITH foF2 = 2.5, 3.0, AND 3.5 MHz LOCATED AT 350 km ALTITUDE

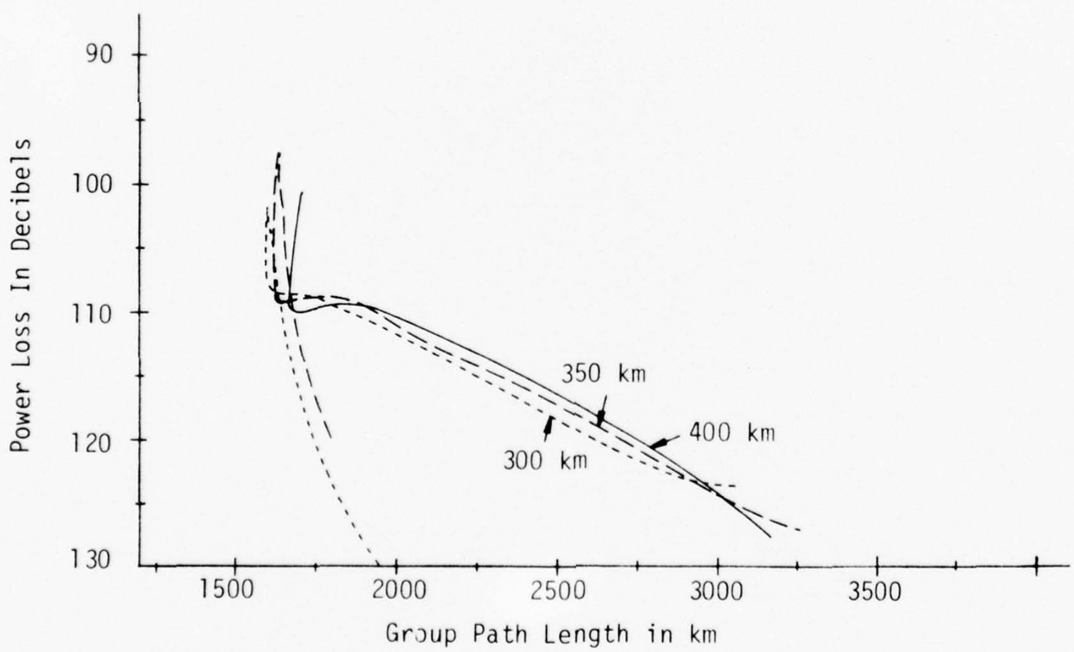


FIGURE 11. POWER LOSS VERSUS GROUP PATH LENGTH FOR SINE SQUARED PROFILES WITH foF2 = 3.0 MHz LOCATED AT 300, 350, AND 400 km

To compare the results derived from the sine squared model with those from a Chapman layer model, rays were traced through a 3.0 MHz Chapman layer with scale height of 67.5 km and with the maximum at heights of 300, 350, and 400 km.
The variation of ground range for a given group path was in the order of 100 km over the three models (Figure 9), three times as sensitive to a 100 km change in h_{max} as the sine squared layer. The case for the maximum at 300 km closely followed the 3.0 MHz sine squared standard which was used. The power loss variation for a given group path varied by as much as 8 dB and was considerably different in appearance from the sine squared curves (Figure 12). Again the 300 km case most strongly resembled the sine squared standard.

The chosen sine squared model thus produces results which are less sensitive to h_{max} or foF2 changes than those derived from a Chapman model.

3.2 Power Loss Calculations

Power loss calculations were for backscattered power returned from ground reflections for the area covered by a beam 1^o in elevation and 1^o in azimuth.

The power returned, P_r, is given by:

$$P_r = \frac{P_o \lambda^2}{4\pi} \cdot \left(\frac{\Delta S}{A_p}\right)^2 \cdot \sigma \cdot \frac{P_w}{2\sigma_t}$$

where P_o is the transmitted power.

The quantity used as the power loss in db is actually

$$10 \log_{10}\left(\frac{P_r}{P_o}\right) = 10 \log_{10}\left(\frac{\lambda^2}{4\pi}\right) + 20 \log_{10} \frac{\Delta S}{A_p} + 10 \log_{10}\sigma + 10 \log_{10}\left(\frac{P_w}{2\sigma_t}\right)$$

where λ is the wave length in km.

$\frac{\Delta S}{A_p}$ is the ray spreading

σ is the backscatter cross-section

P_w is the pulse width (50 km. was used)

σ_t is the rms group path deviation.

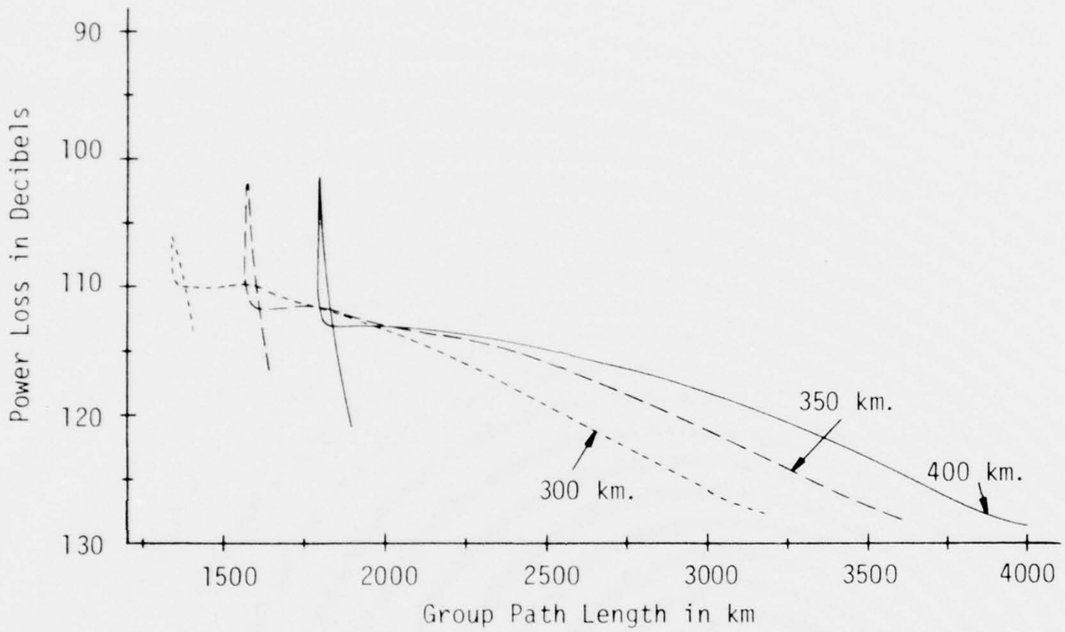


FIGURE 12. POWER LOSS VERSUS GROUP PATH LENGTH FOR CHAPMAN PROFILES WITH foF2 = 3.0 MHz LOCATED AT 300, 350, AND 400 km

Other power loss factors which are not included at the present time are: absorption, transmitter and receiver gain. Absorption was not considered in these model computations, since it would not impact differently on rays propagated via a disturbed or a smooth ionosphere. The transmitter and receiver antenna patterns may be readily imposed as a function of frequency, azimuth, and elevation on the results reported in Section 4. A more detailed discussion of the computation of backscatter and spread losses may be found in Chapter IV of RADC-TR-77-60.

4.0 Significant Observations

Rays were traced through the trough models given in Table 1 and the power differences, range errors, and azimuth deviations were computed. Transmission frequencies used were 4, 5, 6, 7, 8, and 9 MHz. It was found, for the models used, that rays escaped for most elevation angles for frequencies greater than 6 MHz. Trough IV, the model with the weakest gradient and lowest foF2 poleward of the trough wall, also gave poor results for frequencies of 5 and 6 MHz. Rays were traced every degree in elevation from 0 to 30^{o} and for azimuth angles from 26.5^{o} to 42^{o} in the geographic coordinate system. The hypothetical transmitter was located at 44.8^{o}N geographic latitude and 67.8^{o}W geographic longitude. The dipolar geomagnetic pole was assumed located at 78.565^{o}N latitude and 69.761^{o}W longitude. Azimuth angles of 41^{o} and greater were unaffected by the trough wall.

Using Trough Models II (weakest gradient, lower quartile), I (median) and III (strongest gradient, upper quartile), the effects of an increase in the trough wall steepness on focusing and defocusing can be shown. Figure 14 a, b, and c shows the difference of the backscatter power derived from the realistic trough wall model and that derived from the horizontally stratified 3 MHz model as a function of elevation angle and azimuth angle of the launched ray. In general, the power compared to the 3 MHz standard ionosphere is enhanced over a wide region for Trough II while this enhanced region becomes increasingly narrow in azimuth as the trough wall steepens to Trough III and an ever increasing area of power degradation appears although most relative losses are less than 10 dB.

Relative enhancement of power is greatest for those azimuth angles where the rays just graze the trough wall. This is in part due to the fact that rays heading more directly into the trough wall are bent down fairly sharply giveing a group path length which is nearer to the 3.0 MHz skip distance. Even though these backscatter signals do have a power comparable to the more grazing rays, they show less power returned if compared with the horizontally stratified model.

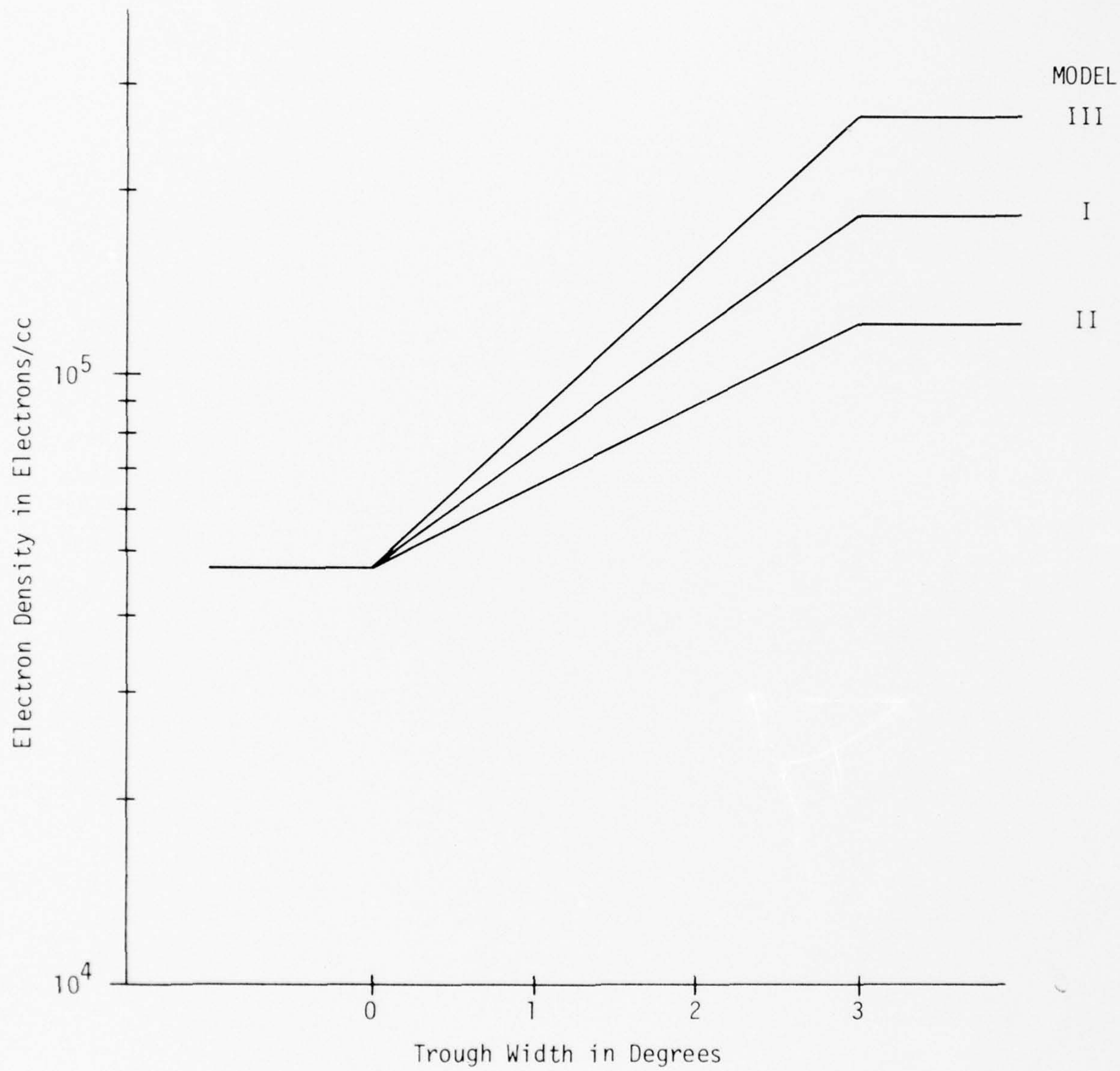


FIGURE 13. MEDIAN TROUGH AND GRADIENT RANGE

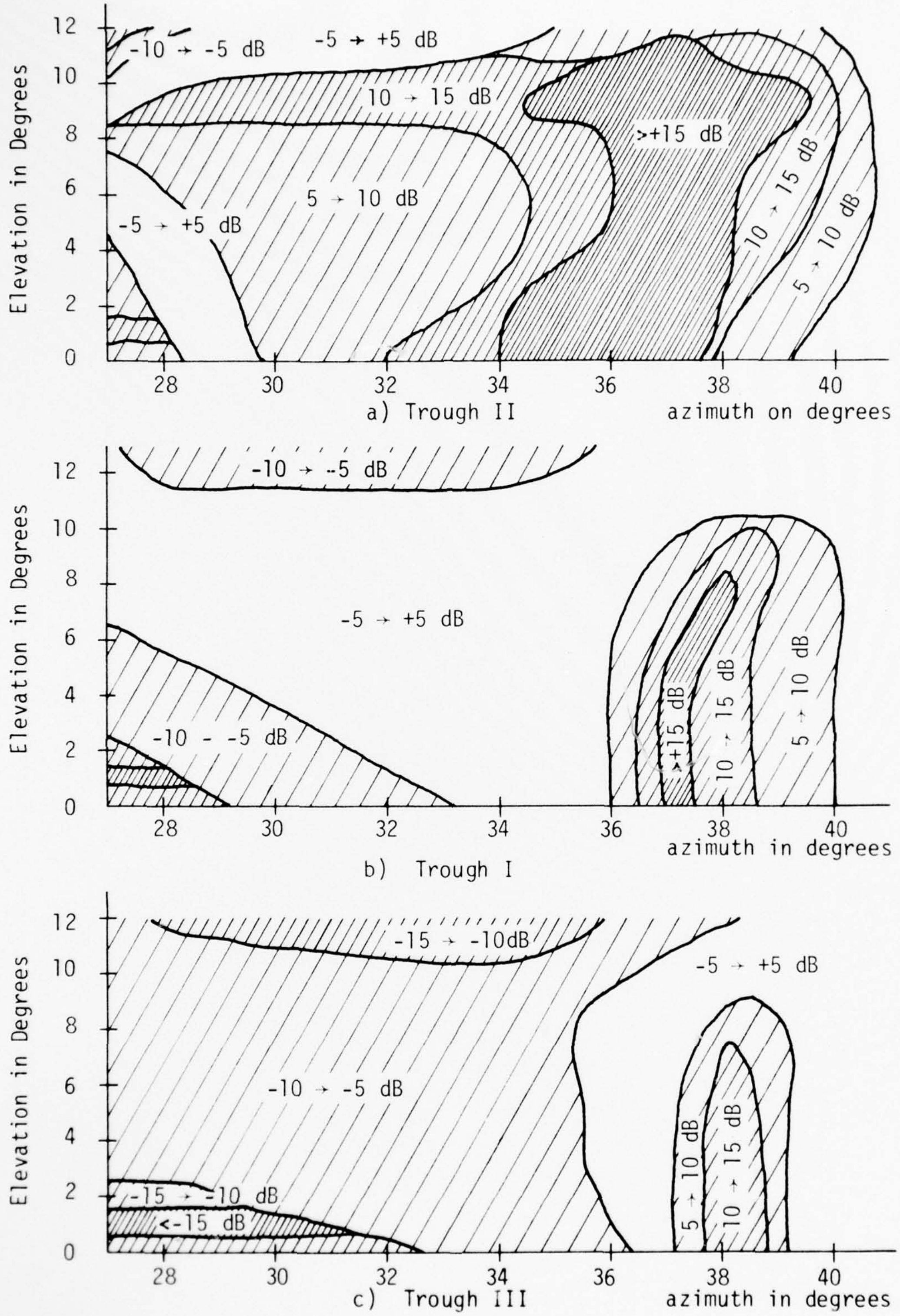


FIGURE 14. POWER LOSS DIFFERENCE WITH 3 MHz FOR SAME GROUP PATH, FREQ. 5 MHz

Rays which escape the effects of the trough wall (those having azimuth angles greater than approximately 41°) experience an apparent enhancement of power if the 3MHz reference model is used. This occurs because, in fact, these rays travel through a 2 MHz horizontally stratified ionosphere. In order to eliminate this false enhancement a 2 MHz reference is used for these rays and for rays which may be slightly influenced by the trough wall but which for the most part travel in the 2MHz ionosphere. Thus for all rays with azimuth angles greater than 39°, the 2 MHz reference is used.

The range and azimuth errors shown in Figures 15 and 16 show a behavior similar to one another in that large range errors generally occur for the same azimuth and elevation angles as large azimuth deviations. Range errors decrease with increasing wall steepness mainly due to the fact that rays are bent more sharply downwards and hence travel less far in a direction tangential to the transmitter. The azimuthal deviation also decreases with increasing wall steepness up to a point although rays are bent sideways more sharply as the steepness increases. This is again due to the fact that rays travel farther after they are bent by a weak trough wall. However, as the trough wall continues to increase in steepness, although rays travel less far after bending, they are bent so sharply sideways that the overall azimuth deviation increases.

This behavior can be more clearly understood by looking at the ray paths as a function of range and azimuth from the transmitter which are shown for Troughs II, I, and III in Figures 17, 18, and 19 respectively. The elevation angle in these figures is 7°. For the azimuth angle 35°, the azimuth deviations, range errors, and total ground range are given in Table 2.

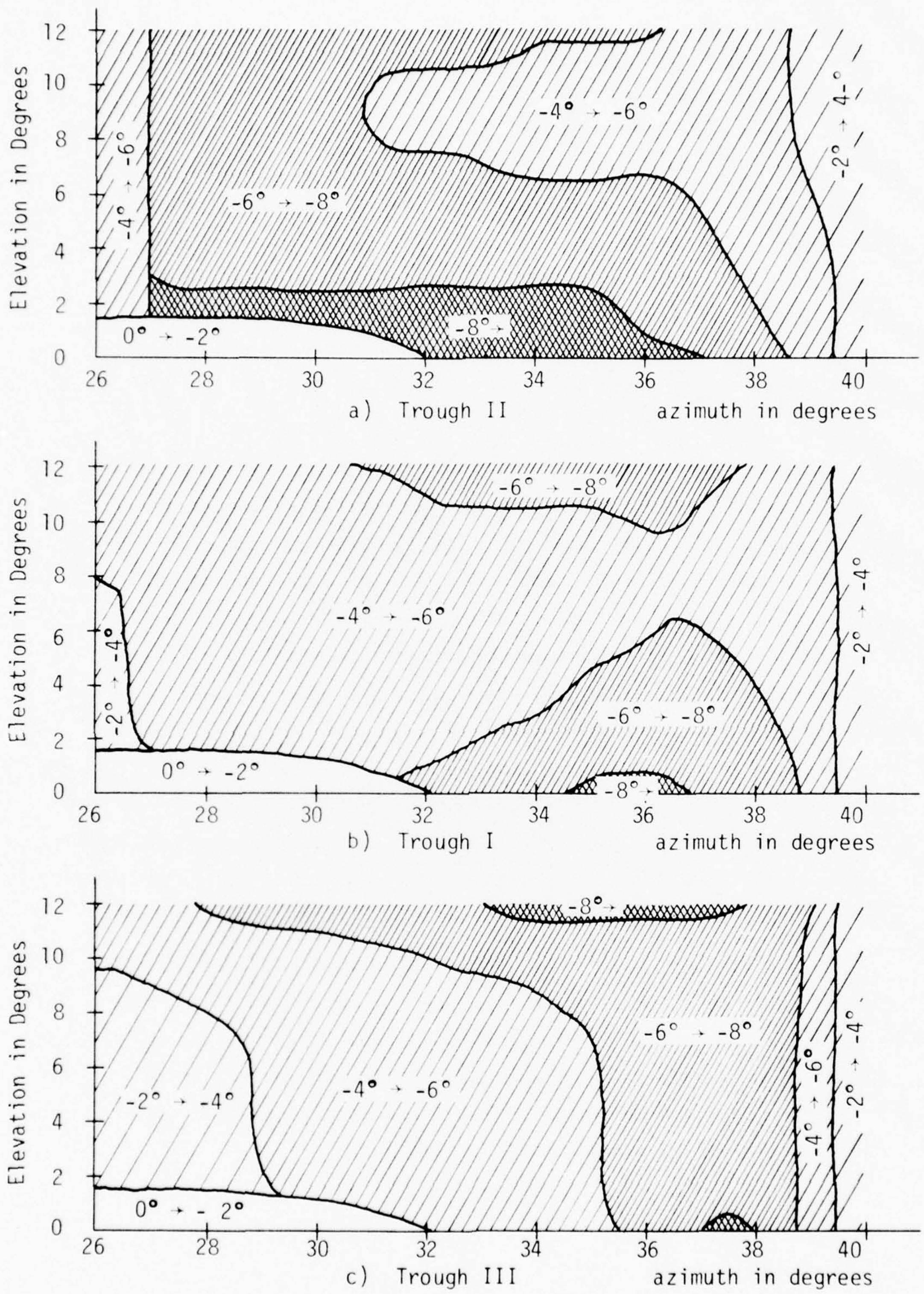


FIGURE 15. AZIMUTHAL DEVIATION AS A FUNCTION OF ELEVATION AND AZIMUTH FOR 5 MHz

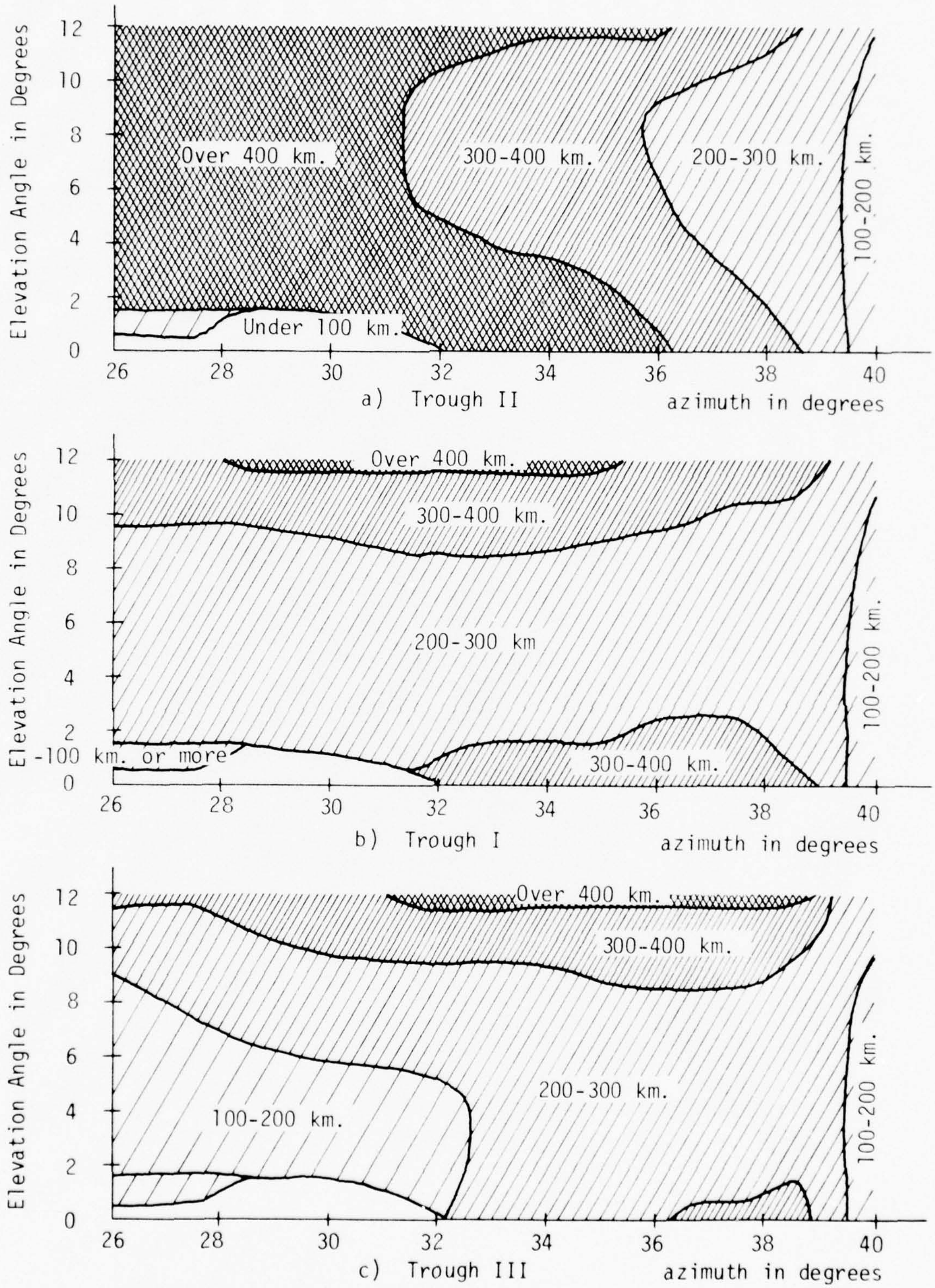


FIGURE 16. RANGE ERRORS USING 3.0 MHz STANDARD FOR 5 MHz TRANSMISSION FREQ.

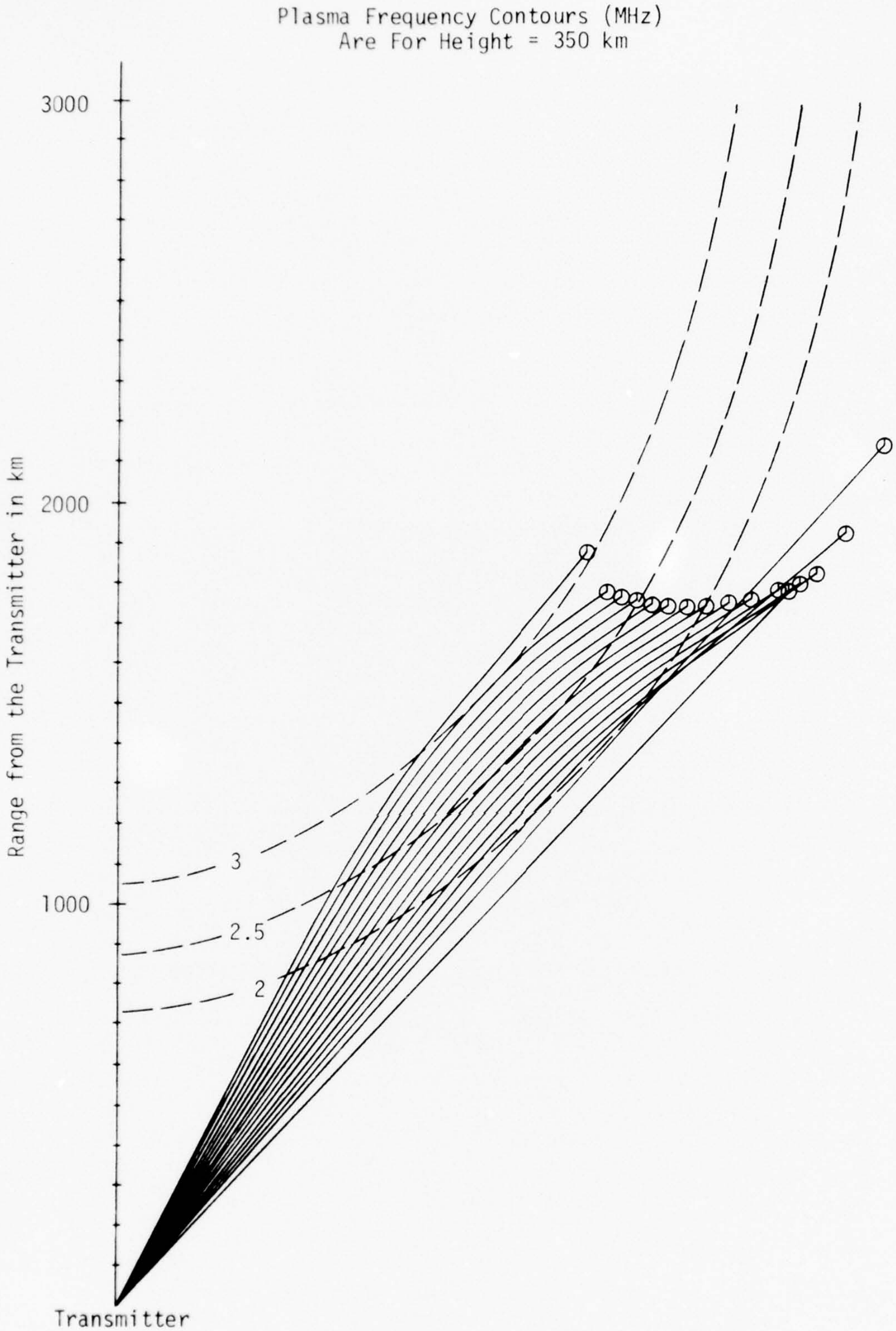


FIGURE 17. RAY PATHS PLOTTED AS A FUNCTION OF RANGE AND AZIMUTH FROM THE TRANSMITTER FOR 7° ELEVATION ANGLE, TRANSMISSION FREQUENCY 5 MHz, AND IONOSPHERIC MODEL TROUGH II

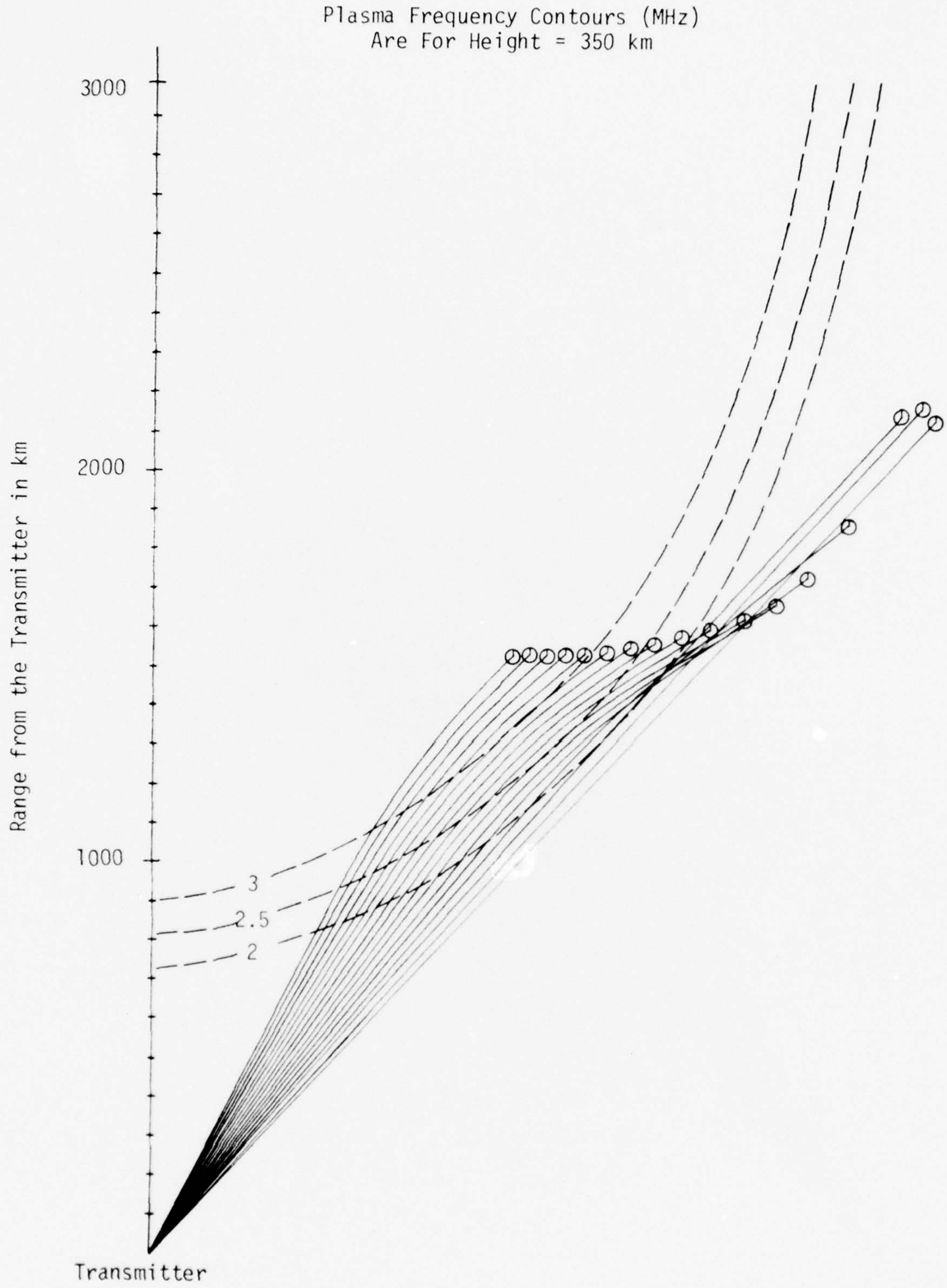


FIGURE 18. RAY PATHS PLOTTED AS A FUNCTION OF RANGE AND AZIMUTH FROM THE TRANSMITTER FOR 7° ELEVATION ANGLE, TRANSMISSION FREQUENCY 5 MHz, AND IONOSPHERIC MODEL TROUGH I

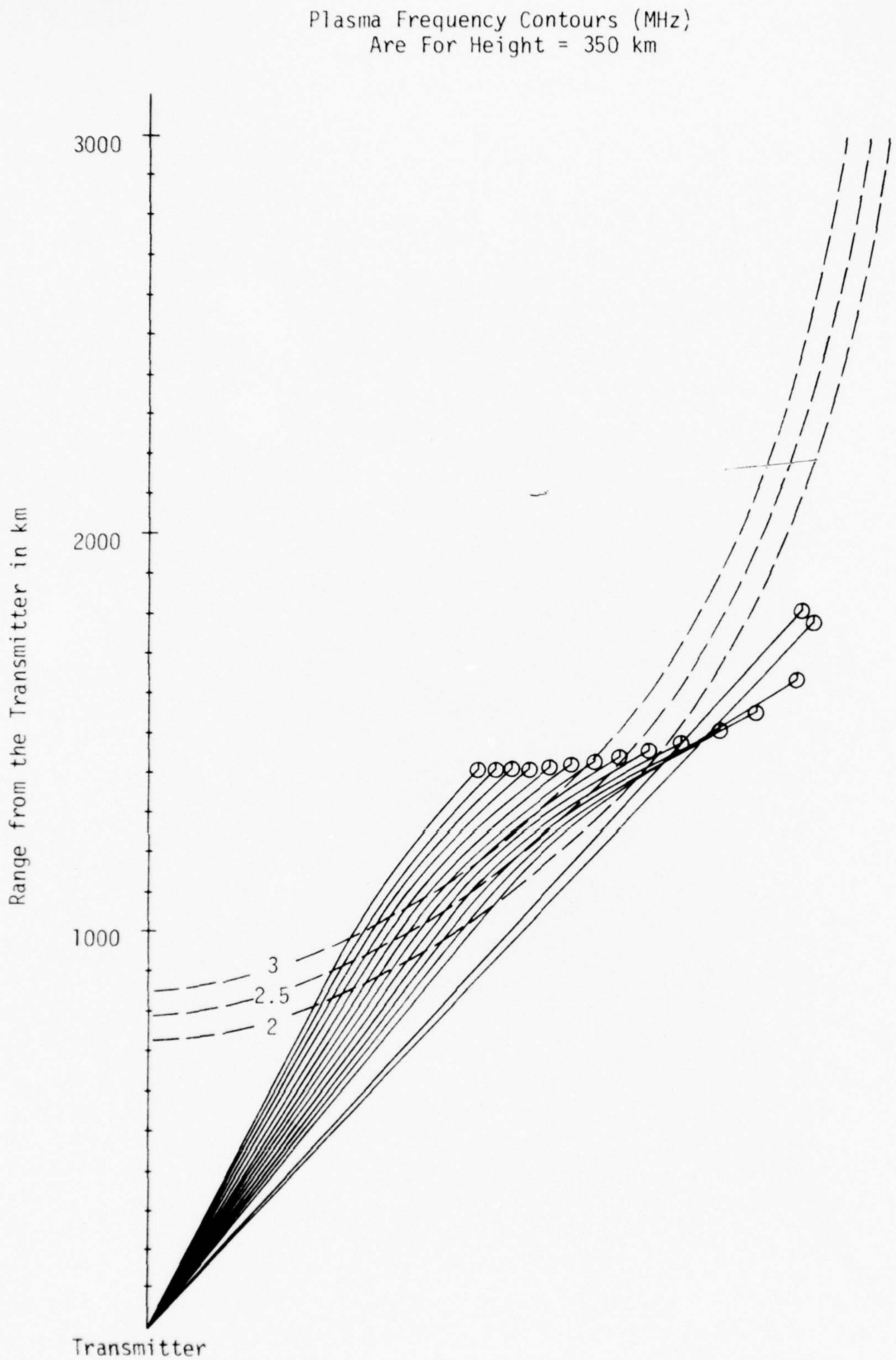


FIGURE 19. RAY PATHS PLOTTED AS A FUNCTION OF RANGE AND AZIMUTH FROM THE TRANSMITTER FOR 7° ELEVATION ANGLE, TRANSMISSION FREQUENCY 5 MHz, AND IONOSPHERIC MODEL TROUGH III

Table 2. Comparison of Azimuth Deviations and Range Errors for Three Trough Models at Elevation Angle - 7^o, Azimuth Angle - 35^o, and Frequency - 5 MHz.

Model	Azimuth Deviation in degrees	Range Error in km.	Ground Range in km.	Ground Reflection Azimuthal Angle
II	-5.8	300	2348	50.88
I	-5.6	270	2115	51.47
III	-5.9	270	1962	53.87

The ground reflection azimuthal angle given in Table 2 is the azimuth angle East of North geomagnetic at which the ray was traveling when a ground reflection occurred. In this case, while the ray for Model II was bent to an azimuth angle less than Model I, its azimuth deviation was greater due to the increased ground range gained (particularly that gained after off great circle bending). However, for Model III the azimuth angle to which the ray was bent was great enough that there was an increase in azimuth deviation over Models II and I even though the ray went less far.

5.0 Conclusions

For the great majority of the rays examined the power return from targets located at their landing points should be great enough to allow detection, if detection at the same frequency under smooth ionospheric conditions would have been possible. The assumptions made about the target's position, if a trough model is not considered in such a determination, could be off in range by up to 500 km and have an azimuth deviation of up to 9^o (the equivalent of 270 km at the ranges we are considering). If a trough model is considered, target positions are still strongly dependent on the chosen trough wall gradient. Ranges vary from +100 to -50 km relative to ranges derived from the median model, if the gradient is changed to the lower quartile or the upper quartile value respectively.

There is also a region close to the trough wall boundary where multi-path occurs thus giving rise to the appearance of two targets where one actually exists.

6. References

Langworthy, B.M., and T.B. Barrett (1975) Implements and Techniques for the Analysis of Radio Propagation Through the Arctic Ionosphere Using Three-Dimensional Ray Tracing, AFCRL-TR-75-0319, Hanscom AFB, Mass.

Langworthy B., T. Barrett, D. Bandes, and L. Calabi (1977) Analysis and Synthesis of Model Ionograms Using 3-D Ray Tracing Techniques, RADC-TR-77-60, Griffiss AFB, New York.

Pike, C.P., (1976) An Analytical Model of the Main F-Layer Trough, AFGL-TR-76-0098, Hanscom AFB, Mass.

APPENDIX A

NAME:	WALL, revision 0, program, PML 152
CATEGORY:	Preprocessing program for use with ray-tracing programs
TITLE:	Trough wall preprocessing program for subroutine BCHAP
LANGUAGE:	CDC extended Fortran - version 4
PROGRAMMER:	B.M. Langworthy, Parke Mathematical Laboratories, Inc.
DATE:	October 21, 1976

DESCRIPTION

Program WALL accepts coordinates of a path in the geographical coordinate system which specifies the poleward side of the arctic trough bottom. It then converts these points to the dipolar geomagnetic system and computes certain quantities needed in the computation of plasma frequency by ray-trace subroutine BCHAP. These quantities are put out on a tape or permanent file for use by the ray-trace program.

INSTRUCTION SET

To use program WALL, the following data must be entered:

Card 1 (A10)

NAME - This is a 10-character alphanumeric name for the trough wall. It will be used by subroutine BCHAP as an electron density subroutine name and will appear on each page of ray-trace output. This name must be punched in columns 1 through 10.

Card 2 (2F10.2) GLAT(1), GLON(1)

GLAT(1) is the geographic latitude in degrees of the first point. GLON(1) is the geographic longitude in degrees of the first point. GLAT must be punched in columns 1 to 10 and must contain a decimal point. GLON must be punched in columns 11 to 20 and must also contain a decimal point.

Cards 3 and on

contain subsequent points along the trough wall and data should be entered in the same manner as on Card 2.

Output from program WALL includes printed output and an unformatted tape or permanent file refered to as TAPE6. TAPE6 is described under FILE DESCRIPTIONS. A sample of the printed output is shown in Attachment 1. For each input point the following information is given:

GLAT - the geographic latitude of the point in degrees

GLON - the geographic longitude of the point in degrees

Θ - the dipolar geomagnetic colatitude in degrees

φ - the dipolar geomagnetic longitude in degrees

a - the length in degrees of the great circle segment connecting (θ, φ) with the next point

β - the azimuth angle in degrees of the great circle segment connecting (θ, φ) with the next point

δ - one half the angle in degrees formed by the two great circles which meet at (θ, φ)

The message "TAPE6 HAS BEEN WRITTEN" will appear after the table to indicate that the program has completed writing TAPE6.

STORAGE REQUIRED

Program WALL requires 40000 octal words of core storage.

ALGORITHM

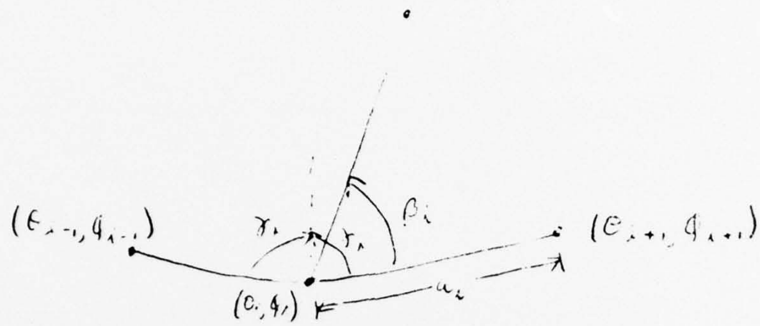
Points inputted in the geographic coordinate system are converted to points (θ_i, φ_i) where:

Θ_i is the dipolar geomagnetic colatitude of the i^{th} entry

φ_i is the dipolar geomagnetic longitude of the i^{th} entry

Several other quantities are computed at this point which are useful for electron density subroutine BCHAP. They are a_i, β_i, and δ i which are defined and illustrated on the following page.

North pole



$$a_i = \cos^{-1}(\cos \theta_i \cos \theta_{i+1} + \sin \theta_i \sin \theta_{i+1} \cos(\phi_{i+1} - \phi_i))$$

$$\beta_i = \cos^{-1}\left(\frac{\cos \theta_{i+1} - \cos \theta_i \cos a_i}{\sin \theta_i \sin a_i}\right)$$

If $i > 1$

$$a_{13i} = \cos^{-1}(\cos \theta_{i-1} \cos \theta_{i+1} + \sin \theta_{i-1} \sin \theta_{i+1} \cos(\phi_{i+1} - \phi_{i-1}))$$

$$\gamma_i = 1/2 \cos^{-1}\left(\frac{\cos a_{13i} - \cos a_{i-1} \cos a_i}{\sin a_{i-1} \sin a_i}\right)$$

$$\beta_{13i} = \cos^{-1}\left(\frac{\cos \theta_{i+1} - \cos \theta_{i-1} \cos a_{13i}}{\sin \theta_{i-1} \sin a_{13i}}\right)$$

If $\beta_{13i} > \beta_{i-1}$, $\gamma_i = \pi - \gamma_i$

If $i = 1$, $\gamma_i = \frac{\pi}{2}$

If i = NENT or the last entry, $a_i = 1$ radian, $\beta_i = \frac{\pi}{2}$, and $\gamma_i = \frac{\pi}{2}$.

SPECIAL CAUTIONS AND FEATURES

The number of point entries should not exceed 60.

TIMING

Execution time is .05 seconds for 10 points

ERROR MESSAGES

THERE IS NO INPUT DATA.

This message will be printed in data cards if point entries are inadvertently omitted.

SUBROUTINES

DICOORD - The subroutine converts points from the geographic to the dipolar geomagnetic system.

ACCURACY

The accuracy of the trough wall outputted by WALL is dependent on the accuracy and closeness of the input points.

FILE DESCRIPTIONS WALL(INPUT,OUTPUT,TAPE4=INPUT,TAPE6)

Program WALL writes data onto TAPE6 to describe the trough wall to subroutine BCHAP. TAPE6 contains the following data in unformatted form.

Record 1	NAME,NENT	
	NAME	- an alphanumeric name for the wall data set
	NENT	- the number of entry points (≤ 30)
Record 2	(DCLAT(i), i = 1,NENT)	
	DCLAT	- array of dipolar geomagnetic colatitudes in radians
Record 3	(DLON(i), i = 1,NENT)	
	DLON	- array of dipolar geomagnetic longitudes in radians
Record 4	(SDA(i), i = 1,NENT)	
	SDA	- length of great circle segments connecting points in radians
Record 5	(BETA(i), i = 1,NENT)	
	BETA	- the azimuth angle of the line segment in radians
Record 6	(GAM(i), i = 1,NENT)	
	GAM	- one half the angle between consecutive segments in radians

DECK SETUP

```
LANWG,T10,CM50000.                      NO.      NAME
FTN.
REQUEST(TAPE6,*PF)
LGO.
CATALOG(TAPE6,UT06WALLX3693818,ID=LANGW,RP=999)
7/8/9
  Deck of program WALL and subroutine DICOORD
7/8/9
  Data cards
6/7/8/9
```

TROUGH WALL OUT

GEOG LATITUDE	GEOG LONG.	DIP COLAT.	DIP LONG.	SIDE A	BETA	GAMMA
51.500	295.000	27.119	6.500	3.238	72.112	90.000
52.510	300.000	26.292	13.470	3.232	70.577	88.120
53.700	305.000	25.368	20.595	3.360	64.781	87.687
55.400	310.000	24.112	28.027	3.506	64.403	86.643
57.200	315.000	22.667	35.718	3.551	57.735	83.139
59.600	320.000	21.174	44.156	3.354	66.375	87.454
61.900	325.000	19.723	52.722	3.290	60.664	86.083
64.300	330.000	18.325	61.890	2.891	67.781	89.221
66.300	335.000	17.432	70.851	2.709	70.986	87.336
68.200	340.000	16.741	79.787	57.290	90.000	90.000

TAPEE HAS BEEN WRITTEN.

<u>Attachment 1</u>. Sample Output from Program WALL

APPENDIX B

NAME:	BCHAP, revision 0, subroutine, PML 151
CATEGORY:	Electron density subroutine for Ray-Tracing Program
TITLE:	Double Chapman Layer for Trough Simulation
LANGUAGE:	CDC Extended Fortran - version 4
PROGRAMMER:	B.M. Langworthy, Parke Mathematical Laboratories, Inc.
DATE:	October 21, 1976

DESCRIPTION

The electron density model, BCHAP, is a replacement for electron density subroutine CHPTRH, PML 128. Whereas in subroutine CHPTRH, the trough wall was located along a line of constant dipolar geomagnetic colatitude, subroutine BCHAP can use an arbitrary trough wall orientation. The electron density model is a double Chapman layer with variations as a function of perpendicular distance from the trough wall. At present the only Chapman layer parameters which vary are the critical frequencies of the two layers. The layer height and thickness of both layers remain fixed. The location of the trough wall and other parameters needed by subroutine BCHAP are supplied on input TAPE6. This file is created by program WALL, PML 152.

INSTRUCTION SET

The use of CHPTRH is similar to that of other electron density subroutines used by the ray-trace program. In the event that the selective load method described in PML 121 and AFCRL-TR-75-0319 is being used, the SLOAD card will be:

SLOAD(BSUBS,BCHAP, and any desired magnetic field, collision
frequency, and perturbation subroutines)

No auxiliary subroutines are required by subroutine BCHAP.

Input required by the subroutine is in two forms. First, the location of base of the trough wall is defined by coordinates given on TAPE6. This information is explained in detail under FILE DESCRIPTIONS. For further information on it, refer to PML 152 which describes the process of generating TAPE6. The other information required by subroutine BCHAP is input to the

W-array of the ray-trace program. Three locations must be defined as follows:

W-array location	Quantity	
101	F2MX	The maximum plasma frequency of the F2 layer in MHz at the top of the trough wall.
102	F2MN	The maximum plasma frequency of the F2 layer in MHz at the bottom of the trough.
103	PMAX	The width in radians of the trough wall. If PMAX is entered in degrees, a "1" must be placed in column 18 of the input card.

Subroutine BCHAP uses the following information from the ray-trace program:

R(1) - r - radius in km.

R(2) - θ - dipolar geomagnetic colatitude in radians.

R(3) - ϕ - dipolar geomagnetic longitude in radians.

EARTHR - (also W(2)) the radius of the earth in km.

F - (also W(3)) the transmission frequency in MHz.

PI - π -
PIT2 - 2π -
PID2 - $\frac{\pi}{2}$ -
constants.

The subroutine then returns the following quantities:

MODX(1) - an alphanumeric identifier which is supplied by TAPE6. identifying the location of the trough wall.

X - refractivity due to plasma frequency (dimensionless).

PXPR - partial derivative of refractivity with respect to the radius (/km).

PXPTH - partial derivative of refractivity with respect to colatitude (/radian).

PXPPH - partial derivative of refractivity with respect to longitude (/radian).

HMAX - the maximum height of the electron density in km. (This is used to determine when penetration has occured.)

STORAGE REQUIRED

Subroutine BCHAP requires 700 octal words. When used in the ray-tracing program with index of refraction AHWFNC and magnetic field DIPOLY, 50000 octal words are required.

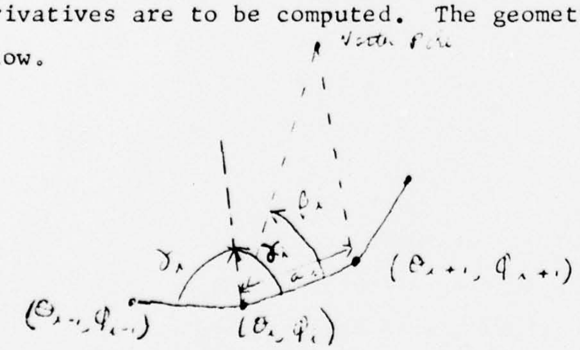
ALGORITHM

The plasma frequency (or electron electron density) model given by BCHAP can be broken into three separate computational areas:

1) computation of wall location parameters; 2) computation of perpendicular distance from the wall and angular components relative to the wall; and 3) computation of the trough wall and the vertical profile. The first area of computation is performed by program WALL but will be briefly presented here since the definition of terms will be needed subsequently.

1) Computation of wall location parameters

The great circle segments which give the location of the trough wall are specified by their endpoints in the dipolar geomagnetic system. The i th endpoint will be referred to by (θ_i, ϕ_i) where θ is the dipolar magnetic colatitude and ϕ is the dipolar magnetic longitude. The point (θ, ϕ) without subscripts is the point for which the plasma frequency and its derivatives are to be computed. The geometry of the situation is given below.



The quantities which will be needed for later computations are:

a_i - the great circle path length in radians between points i and i + 1.

β_i - the clockwise positive angle in radians with vertex at point i between due north and the path connecting points i and i+1.

γ_i - one half the angle in radians formed by points i-1, i, and i+1.

Excluding exceptions for end points,

$$a_i = \cos^{-1}(\cos\theta_i \cos\theta_{i+1} + \sin\theta_i \sin\theta_{i+1} \cos(\phi_{i+1} - \phi_i))$$

$$\beta_i = \cos^{-1}\left(\frac{\cos\theta_{i+1} - \cos\theta_i \cos a_i}{\sin\theta_i \sin a_i}\right)$$

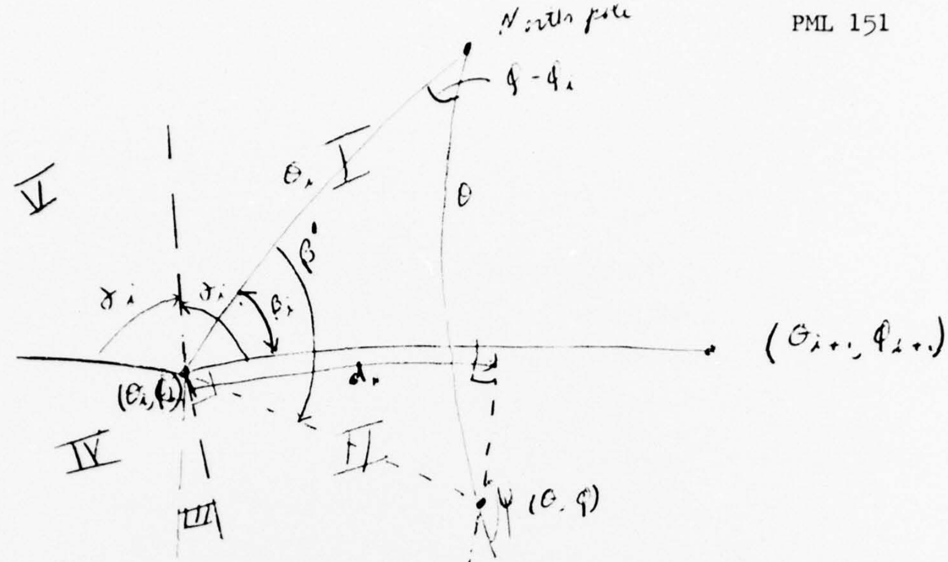
$$\gamma_i = 1/2 \cos^{-1}\left(\frac{\cos a' - \cos a_{i-1} \cos a_i}{\sin a_{i-1} \sin a_i}\right)$$

where $\cos a' = \cos\theta_{i-1} \cos\theta_{i+1} + \sin\theta_{i-1} \sin\theta_{i+1} \cos(\phi_{i+1} - \phi_{i-1})$

2) Computation of the perpendicular distance from the wall to point (θ,ϕ)

To eliminate any ambiguity, perpendicular distance from the wall, P, will be considered positive if the point (θ,ϕ) is on the north poleward side of the wall and negative if it is on the other side. Since all points except those lying on a given great circle will have at least two perpendiculars to the great circle, it must be stated that the perpendicular must occur with the segment of any great circle which forms a part of the trough wall. There may also be cases where there is no such perpendicular due to "kinks" in the wall where two segments join. The first problem, then, is that of finding the proper great circle segment.

To find P, the distance from the curve, and ψ, the angle with respect to positive (θ,ϕ), each segment is tried beginning with i = 1 for the first time and beginning with the preceeding i value thereafter.



C = distance from (θ, φ) to (θ_i, φ_i)

$C = \cos^{-1}(\cos\theta_i \cos\theta + \sin\theta_i \sin\theta \cos(\varphi - \varphi_i))$

β' = angle from due north with vertex at (θ_i, φ_i) to (θ, φ)

$$\beta' = \cos^{-1}\left(\frac{\cos\theta - \cos\theta_i \cos C}{\sin\theta_i \sin C}\right)$$

If $\beta' \leq \beta_i$ and $\beta_i - \beta' < \gamma$, then $B = \beta_i - \beta'$, P is positive, proceed to * } Region I

If $\beta' < \beta_i$ and $\beta_i - \beta' \geq \gamma$, then try next lowest segment. } Region V

If $\beta' < \beta_i$ and $\beta' - \beta_i \leq \frac{\pi}{2}$, then $B = \beta_i - \beta'$, P is negative, proceed to * } Region II

If $\beta' < \beta_i$ and $\frac{\pi}{2} \leq \beta' - \beta_i \leq \frac{3\pi}{2} - 2\cdot\gamma_i$, then $B = \beta_i - \beta'$, $P = C$, proceed to * } Region III

If $\beta' > \beta_i$ and $\beta' - \beta_i > \frac{3\pi}{2} - 2\gamma_i$, then next lowest segment } Region IV

* $P = \sin^{-1}(\sin B \sin C)$

d_1 = distance along the great circle connecting (θ_i, φ_i) and $(\theta_{i+1}, \varphi_{i+1})$ to the perpendicular from (θ, φ)

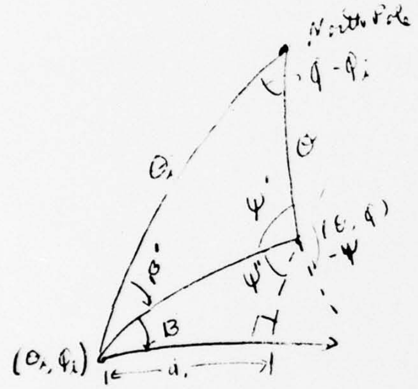
$$d_1 = \cos^{-1}\left(\frac{\cos C}{\cos P}\right)$$

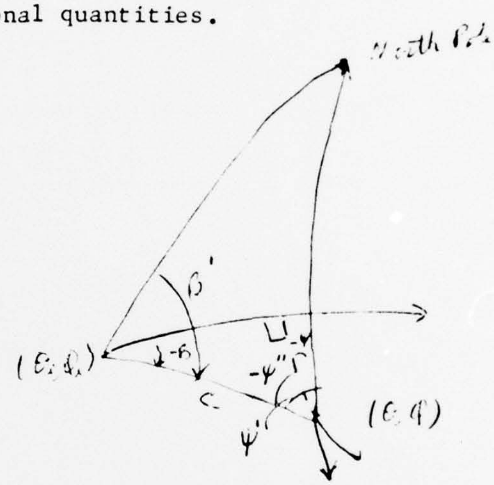
If $d_1 > a$, the perpendicular does not fall within the desired segment and the next highest (in i) segment is tried.

If the perpendicular occurs below the point (θ_1, φ_1), the segment is taken along a constant latitude of θ_1. Here $P = \theta_1 - \theta$ and

$$d_1 = -\cos^{-1}\left(\frac{\cos C}{\cos P}\right)$$

To find ψ, the angle between the perpendicular, P, and the positive θ direction, we compute two additional quantities.





$$\psi' = \cos^{-1}(-\cos(\varphi - \varphi_i)\cos\beta' + \sin(\varphi - \varphi_i)\sin\beta' \cos\theta_i)$$

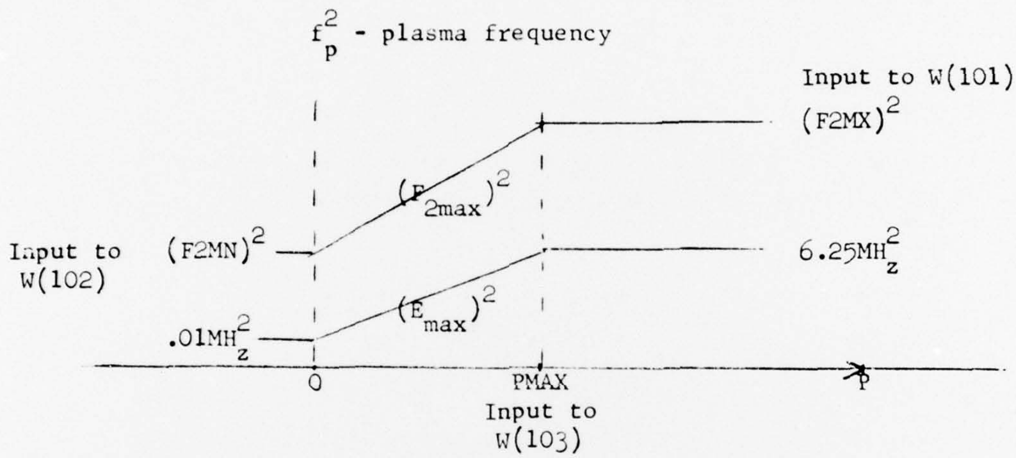
$$\psi'' = \cos^{-1}(\sin B \cos d_1)$$

$$\psi = -\psi'' - \psi'$$

For the region below (θ_1, φ_1), $\psi = \pi$

3) Computation of the trough wall and the vertical profile

The trough wall currently in BCHAP varies as a function of P, the perpendicular distance on inputted curve, in the maximum values of the E- and F- layer. At this time the values of height and layer width remain fixed. The height of the E- layer is 120 km and its scale height is 10 km. The height of the F- layer is 350 km. The E- and F- layer variations are given below.



Given P and Ψ from the previous computation we can now compute the plasma frequency and its derivatives at the point (r, θ, ϕ).

$h = r - r_e$ where r_e is the radius of the earth.

If $70 \leq r \leq 120$,

$$f_p^2 = f_{c_1}^2 \exp(1/2\ (1 - Z_1 - e^{-Z_1})) \text{ where } Z_1 = \frac{h - 120.}{10.}$$

$$\frac{\partial (f_p^2)}{\partial r} = f_p^2 \cdot \frac{1}{20}(e^{-Z_1} - 1)$$

$$\frac{\partial (f_p^2)}{\partial P} = \frac{\partial (f_{c_1}^2)}{\partial P} \cdot \exp\ (1/2(1 - Z_1 - e^{-Z_1}))$$

$$\frac{\partial (f_p^2)}{\partial \theta} = \frac{\partial (f_p^2)}{\partial P} \cos \Psi$$

$$\frac{\partial (f_p^2)}{\partial \varphi} = \frac{\partial (f_p^2)}{\partial P} \sin \Theta \sin \Psi$$

If $120 < h \leq 350$,

$$f_p^2 = f_{c_1}^2 + (f_{c_2}^2 - f_{c_1}^2) \sin^2 H$$

$$\text{where } H = \frac{\pi}{2} \; \frac{h - 120.}{230.}$$

$$\frac{\partial (f_p^2)}{\partial r} = \frac{\pi}{230} (f_{c_2}^2 - f_{c_1}^2) \sin H \cos H$$

$$\frac{\partial (f_p^2)}{\partial P} = \frac{\partial (f_{c_1}^2)}{\partial P} + \left(\frac{\partial (f_{c_2}^2)}{\partial P} - \frac{\partial (f_{c_1}^2)}{\partial P} \right) \sin^2 H$$

$$\frac{\partial (f_p^2)}{\partial \Theta} = \frac{\partial (f_p^2)}{\partial P} \cdot \cos \Psi$$

$$\frac{\partial (f_p^2)}{\partial \varphi} = \frac{\partial (f_p^2)}{\partial P} \sin \Theta \sin \Psi$$

$$f_{c_1}^2 = .01 \quad \text{if } P \leq 0$$

$$= .01 + 6.24 \frac{P}{P_{max}} \quad \text{if } 0 < P < P_{max}$$

$$= 6.25 \quad \text{if } P \geq P_{max}$$

$$\frac{\partial f_{c_1}}{\partial P} = \frac{6.24}{P_{max}}$$

$$f_{c_2}^2 = (\text{F2MN})^2 \quad \text{if } P \leq 0$$

$$= (\text{F2MN})^2 + (\text{F2MX}^2 - \text{F2MN}^2) \frac{P}{P_{max}} \quad \text{of } 0 < P \leq P_{max}$$

$$= (\text{F2MX})^2 \quad \text{if } P \geq P_{max}$$

$$\frac{\partial f_{c_2}}{\partial P} = \frac{(\text{F2MX}^2 - \text{F2MN}^2)}{P_{max}}$$

SPECIAL CAUTIONS AND FEATURES

This subroutine as all other electron density subroutines for RAYTRACEBL assumes that values for θ and ϕ are in dipolar geomagnetic or computational coordinates.

If the number of entries from TAPE6 exceeds 30, a new dimension statement must be inserted.

TIMING

For a large number of rays computed using BCHAP execution time was about 1 second per ray. This will aproach 1.7 seconds per ray if only low elevations angles are considered. Timing was done on 1-hop rays at frequencies from 5 to 9 MHZ.

ERROR MESSAGES

None.

SUBROUTINES

No nonsystem subroutines are required.

ACCURACY

The accuracy of the trough in BCHAP is dependent on the closeness and accuracy of the points describing the trough wall on input TAPE6.

FILE DESCRIPTIONS

BCHAP reads data off of TAPE6 during program initialization. TAPE6 contains the following data in unformatted form generated by WALL(PML 152). (Symbols in parentheses refer to symbols used in the algorithm on pages 3-4 .

FILE DESCRIPTIONS (continued)

Record 1 MODX(1), NENT

MODX(1) - an alphanumeric name for the wall data set

NENT - the number of point entries (≤ 30)

Record 2 (TH(i), i = 1,NENT)

TH - array of dipolar geomagnetic colatitudes in radians (θ_i)

Record 3 (PH(i), i = 1,NENT)

PH - array of dipolar geomagnetic longitudes in radians (ϕ_i)

Record 4 (SDA(i), i = 1,NENT)

SDA - length of great circle segments connecting points in radians (a_i)

Record 5 (BETA(i), i = 1,NENT)

BETA - the azimuth angle of the line segment in radians (β_i)

Record 6 (GAM(i), i = 1,NENT)

GAM - one half the angle between consecutive segments in radians (γ_i)

DECK SETUP

Runs using BCHAP would be similar to other ray-trace runs except that a TAPE6 must be attached and the SLOAD card given on page 1 should be used